

IMAGING FATIGUE CRACKS IN LOW CARBON STEELS WITH THE GEL ELECTRODE

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ABSTRACT

The fatigue testing of prototype components is very time consuming. A basic limitation is that conventional techniques cannot detect fatigue cracks until they have grown to several millimeters in length. For aluminum alloys this problem was overcome by the development of the gel electrode method of imaging very small (10^{-2} mm) cracks. This technique has now been modified for applications to steel. A primary requirement is that prior to fatigue testing, the surface is coated with a thin (30 nm) insulating dual-layer oxide/organic film by a two step anodization process. During testing, the film is ruptured if a fatigue crack forms in the steel. When the surface is contacted with a gel electrode, a 4V, 200 ms pulse causes current to flow preferentially to the crack. This current forms an image which is retained in the surface of the gel. This paper is illustrated by images of fatigue cracks in a dual phase steel and a high strength low alloy (HSLA) steel. The images are well defined and can be repeated many times, as required for periodic in situ inspection during component testing. Features of the image are correlated with crack segments only 10^{-2} mm long.

INTRODUCTION

The design and evaluation of the fatigue performance of prototype components can be both time consuming and frustrating. A basic limitation is that conventional inspection techniques cannot detect fatigue cracks smaller than several millimeters in length. So until such a crack has formed, this primary site of fatigue cannot be identified nor the test terminated. Furthermore such a test usually only indicates the need for a single design change, since the secondary sites of fatigue damage cannot be identified until they appear later as primary sites of failure in subsequent designs. This time consuming iterative design and testing process could be abbreviated if all the secondary sites of more subtle fatigue damage could also be detected and assessed.

The gel electrode is the only inspection technique with sufficient sensitivity to identify the very small cracks at the sites of secondary fatigue. The technique was originally developed for aluminum alloys, shown to image cracks only 10^{-2} mm long [1-4], and successfully applied to component testing [5,6]. More recently the technique was modified to detect fatigue cracks in low carbon steel [7]. This paper describes the procedures involved and is illustrated by images of fatigue cracks in two types of higher strength low carbon sheet steels: a dual phase steel

(Inland DPL-80) and a high strength low alloy (HSLA) steel (Inland HI-form 60). The HSLA steel is strengthened by a large concentration of small carbide particles, while the dual phase steel is strengthened by islands of martensite. Thus this investigation also addresses the following question: Will the above mentioned microstructural features influence the gel electrode imaging process?

EXPERIMENTAL

The procedure consists of the following steps. 1) The formation of a thin (30 nm) protective film on the surface of the specimen. 2) Fatigue testing to create fatigue cracks in the steel and, correspondingly, in the protective film. 3) Imaging the fatigue crack by contacting the surface with a gel electrode and applying a voltage pulse.

Specimen Preparation

Specimens 8 cm long and 2 cm wide were cut from sheet material 1.5 mm thick. The HSLA steel has a tensile strength of 500 MPa, while that of the dual phase steel is 600 MPa. A small notch ~1.5 mm deep was filed in both edges of each specimen to localize the process of crack initiation. After degreasing, the specimens were cleaned with Electroclean (McGean and Rocho, Inc.) followed by Oxivate #345 (Udylite Corporation), then rinsed with distilled water and alcohol.

A protective surface film was formed by a two step anodization procedure similar to that described by Leidheiser and Konno [7].

Step I. The specimen was immersed in an electrolyte containing 0.02 M boric acid and 0.005 M sodium borate, and maintained at -2V (SCE)* for five minutes to remove any preexisting oxide film. Then the potential of the specimen was switched to +0.7V (SCE) for one hour to form an anodic oxide film 15 nm thick.

Step II. The specimen was transferred to a second electrolyte and raised to a potential of +1.2V (SCE) for one hour. This second electrolyte differed from the first only in that it also contained 0.004 M 8-hydroxyquinoline (HQ). This produces an additional 15 nm surface film with a light gold color. After each step the specimen was rinsed with distilled water, then alcohol, and blown dry.

Fatigue Testing

The specimens were subjected to fully reversed cyclic loading until a fatigue crack was formed at the root of a notch.

Gel Electrode Imaging

The gel electrode was applied in the manner described previously [6]. The electrolyte consisted of an agar gel containing 0.06 molar potassium iodide (KI) and 0.19 molar starch. This warm fluid mixture was dispensed into small lengths (~30 mm) of plastic tube 6 mm in diameter. The tube was overfilled so that upon cooling the liquid formed a smooth hemispherical and flexible gel tip protruding from one end of the tube. An aluminum wire, inserted into the other end of the tube, served as a cathode. The gel tip was pressed gently against the surface of the specimen and a pulse of negative potential (4V, 200 ms) was applied to the cathode. The images formed in the skin of the gel were viewed and photographed with an optical microscope. The flow of current during image formation was recorded on a Nicolet Digital oscilloscope and the total charge flow obtained by numerical integration with a Hewlett Packard Model 85 computer.

* Potentials are quoted with respect to standard calomel electrode (SCE).

RESULTS

Image Repeatability

Enlarged pictures of gel electrode images of a fatigue crack in the dual phase steel are shown in Fig. 1. This particular crack, which is 0.7 mm long, was produced after 1.8×10^5 cycles. The crack was then imaged sequentially with twelve gel electrodes. Only the first, fifth and twelfth images in this series are shown, but they illustrate the repeatability of the crack detection process. The last image is narrower than the first image, but still provides a clear identification of the crack and the characteristic irregularities of the crack path. The last image also contains a background of small spots, particularly along the edge of the notch and close to the fatigue crack. These spots correspond to sites of breakdown of the surface anodic film due to repeated application of the gel electrode, but their distribution suggests that some of these sites may be related to fatigue deformation in the stress field of the notch.

A similar sequence of images are shown in Fig. 2 for a fatigue crack formed in a HSLA steel specimen after 4×10^5 cycles. In this example, the width of the image appears to increase gradually throughout the sequence due to the development of a high density of spots along each side of the crack, which again are probably related to the presence of deformation. A total of eight well defined images were obtained in this sequence.

Subsequent applications of the gel electrode to the crack in HSLA steel produced only weakly developed images surrounded by many very small dots. This fading of the image from HSLA steel was accompanied by a large increase of current from the gel electrode, whereas there was only a modest increase of current during the sequence of reproducible images from the dual phase steel (Fig. 3). Thus this additional current flows, not to the crack which requires only 10^{-5} coulomb/mm of crack length [3] to form an image, but to defects in the anodic film. Under repeated application of the gel electrode, these defects become sufficiently conductive to contribute a random distribution of background spots to the image (Figs. 1 and 2). When the charge to the defects exceeds $\sim 10^{-3}$ coulomb/cm² the crack is effectively short circuited and no longer imaged. From the

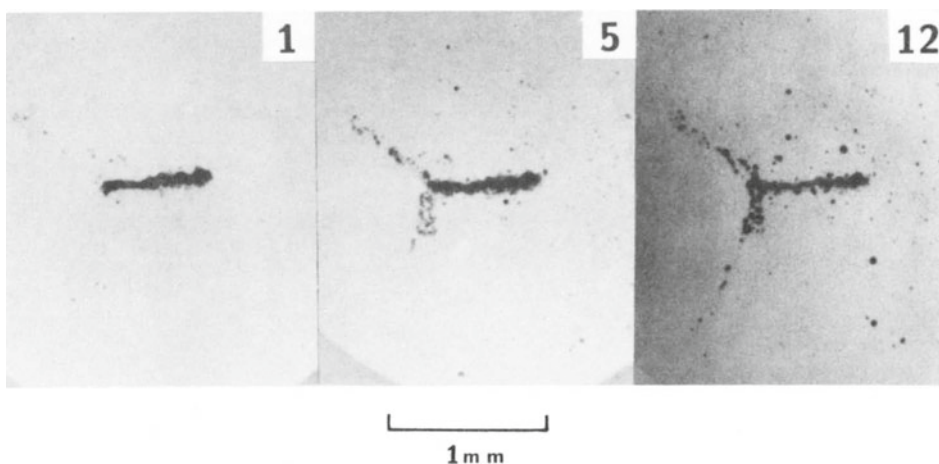


Fig. 1 First, fifth and twelfth in a sequence of gel electrode images of a fatigue crack in a dual phase steel. Each image formed by a 4V, 200 ms pulse.

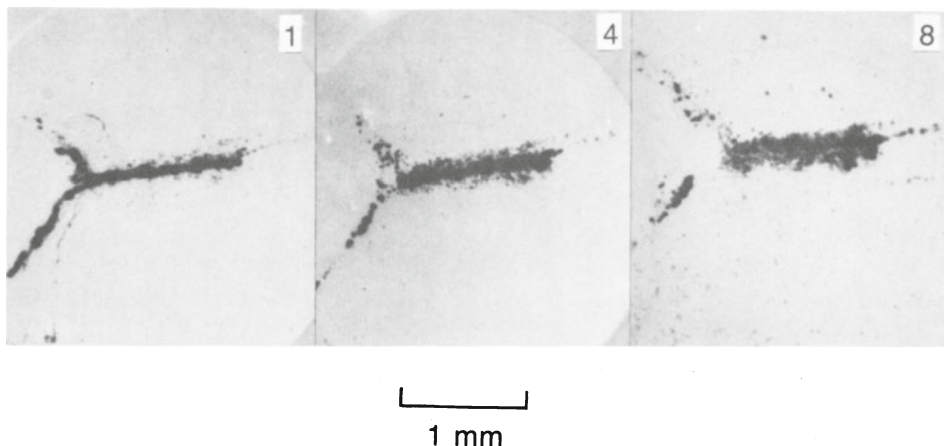


Fig. 2 First, fourth and eighth in a sequence of gel electrode images of a fatigue crack in HSLA steel. Each image formed by a 4V, 200 ms pulse.

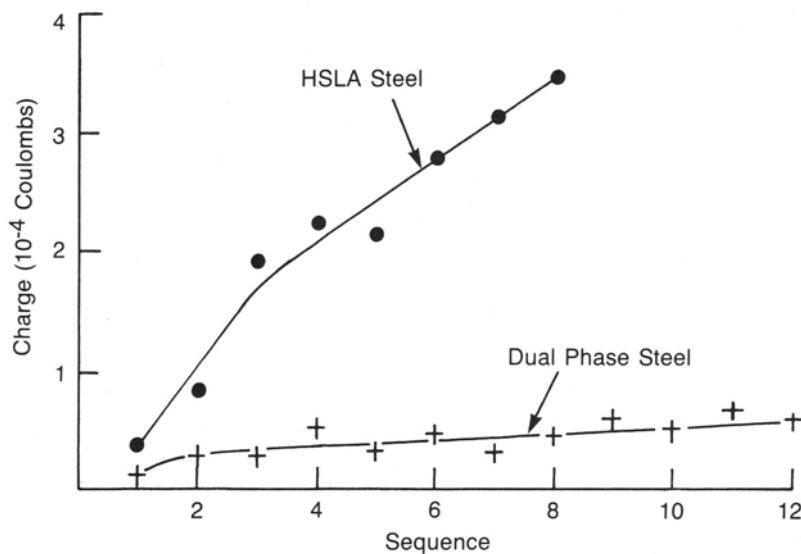


Fig. 3 The charge flow associated with the formation of each image in the sequences illustrated in Figs. 1 and 2. Area of contact of the gel electrode is $\sim 0.1 \text{ cm}^2$.

results of Figs. 1 to 3, we conclude that a protective anodic film forms on both the ferrite and martensite phases in the dual phase steel, but that the film on the HSLA steel contains defects associated with the fine dispersion of small carbide particles.

Image Resolution

All the images shown in Figs. 1 and 2 were formed with a 4V, 200 ms pulse, which provides good image repeatability but greatly exaggerates the width of the crack. Such images have the advantage of being visible to the unaided eye but suffer from the obscuration of detail, limiting the

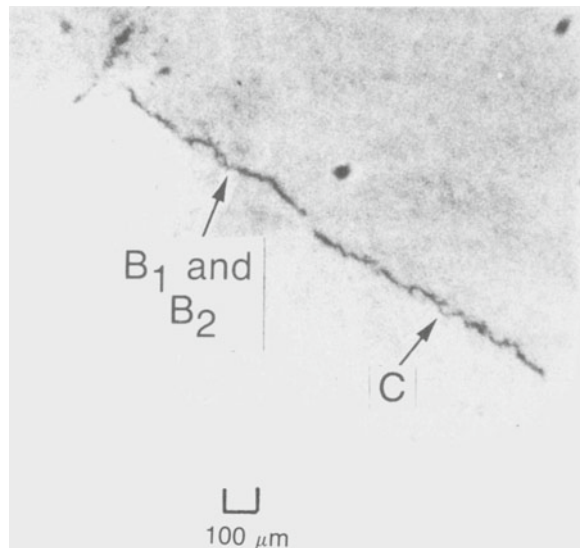


Fig. 4 High resolution gel electrode image of a fatigue crack in HSLA steel. Image formed by a 7V, 10 ms pulse.

spatial resolution to $\sim 50 \mu\text{m}$. To illustrate the microscopic size of the features of a crack which are contributing to the image, it is necessary to form a narrower image by restricting the charge flow. A good example is provided by Fig. 4, which shows an enlarged view of a gel electrode image obtained from a HSLA steel specimen with a 7V, 10 ms pulse. The width of this image is only $\sim 10 \mu\text{m}$, so it can be correlated in a detailed manner with direct observations of the crack itself by scanning electron microscopy. Such a correlation is illustrated by the two scanning electron micrographs in Fig. 5. The two bends in the crack path identified as B_1 and B_2 in Fig. 5(a) correspond to the features similarly labeled in Fig. 4. Similarly, the bend in the main crack and the small branching crack at C in Fig. 5(b) are also resolved in the gel electrode image (Fig. 4). Note that all these geometrical features are formed by crack segments only $\sim 10 \mu\text{m}$ in length.

CONCLUSIONS

1. The gel electrode provides well defined images of fatigue cracks in dual phase and high strength low alloy steels.
2. The images contain contributions from branching cracks and other irregularities of the crack path which are only $\sim 10 \mu\text{m}$ in length. This sensitivity surpasses by far that of commercially available crack detection methods.
3. A crack can be imaged many times: twelve good quality images were obtained from dual phase steel, and eight from HSLA steel. This is certainly sufficient for periodic in situ inspection during a fatigue test, in order to monitor the onset and growth of fatigue cracks.
4. The inability to obtain an infinite number of images is due to the eventual widespread breakdown of the protective anodic film.

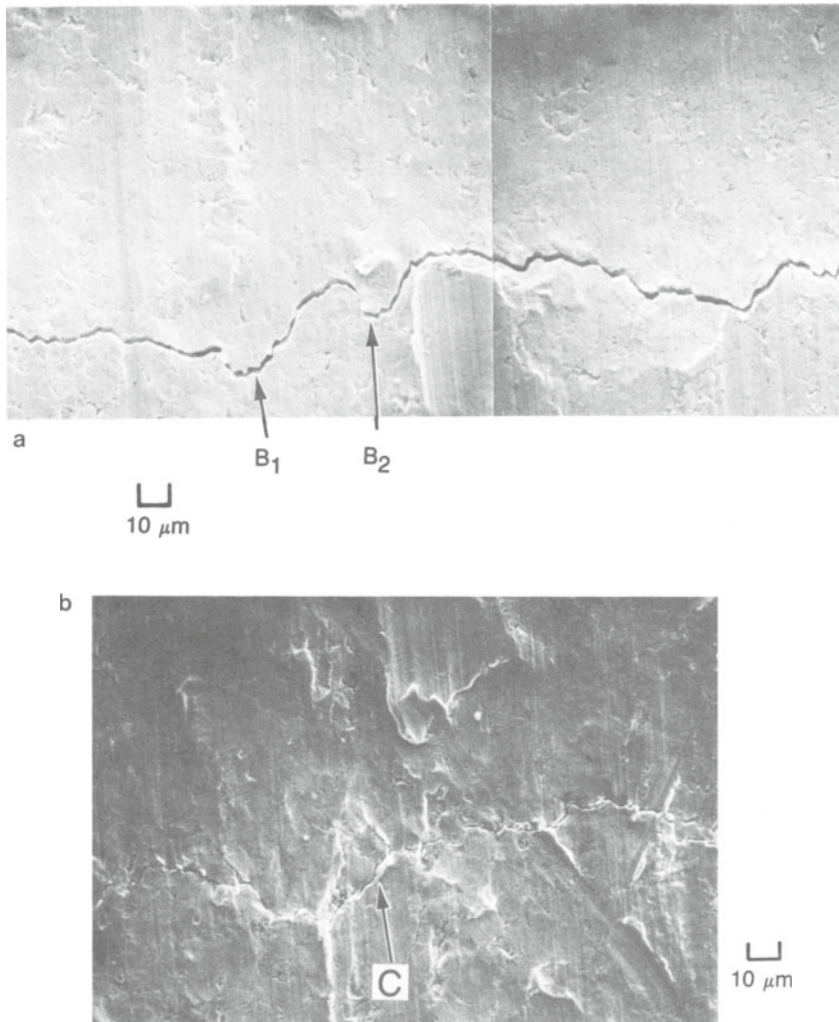


Fig. 5 Scanning electron micrographs of two portions of the crack imaged in Fig. 3. (a) The two bends at location B; (b) The bend and branching crack at location C.

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